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(54) **Method of forming yttria-stabilised zirconia to minimise low-temperature degradation**

(57) The invention is directed to an apparatus and a method of substantially eliminating destructive low-temperature, humidity-enhanced phase transformation of yttria-stabilized zirconia in general, as well as eliminating low-temperature degradation of yttria-stabilized tetragonal zirconia polycrystalline ceramic (Y-TZP). The martensitic-type phase transformation from tetragonal to monoclinic is accompanied by severe strength degradation in a moist environment at low-temperature, specifically at room temperature as well as at body tem-

perature. This class of materials has been chosen as the packaging material for small implantable neural-muscular sensors and stimulators because of the high fracture toughness and high mechanical strength. This destructive phase transformation has been substantially eliminated, thus ensuring the safety of long-term implants, by subjecting the sintered components to post-machining hot isostatic pressing, such that the average grain size is less than about 0.5 microns.

Description

CROSS REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of U.S. Provisional Application Serial No. 60/453,682, filed on March 10, 2003.

FIELD OF THE INVENTION

[0002] This invention relates to an apparatus and a method of increasing the useful life of an yttria-stabilized zirconia structure when implanted in living tissue.

BACKGROUND OF THE INVENTION

[0003] A widely employed bioceramic is alumina, which is classed as bioinert. The search for an ideal bioceramic has included alumina, hydroxyapatite, calcium phosphate, and other ceramics. The first use of aluminas for implants in orthopedics and dentistry was in the 1960's and they were employed in hip prostheses as early as 1970. Since those early days the quality and performance of aluminas have improved and high-purity, high-density, fine-grained aluminas are currently used for a wide range of medical applications, e.g. dental implants, middle ear implants, and hip or knee prostheses.

[0004] Although the aluminas currently available perform satisfactorily, a further improvement in strength and toughness would increase the safety factor and may extend usage to higher stressed components. A proposed candidate to add to this list is stabilized-zirconia because of its potential advantage over alumina of a lower Young's modulus, higher strength, and higher fracture toughness. Another advantage of stabilized-zirconia is low-wear residue and low coefficient of friction. Zirconia undergoes a destructive phase change at 1000° to 1100°C from monoclinic to tetragonal, which necessitates phase stabilization by calcia, magnesia, ceria, or yttria.

[0005] Tetragonal zirconia polycrystalline ceramic, commonly known as TZP, which typically contains 3 mole percent yttria, coupled with the small size of the particles, results in the metastable tetragonal state at room temperature. Under the action of a stress field in the vicinity of a crack, the metastable particles transform, with a 3% to 4% volume increase, by a shear-type reaction, to the monoclinic phase. Crack propagation is retarded by the transforming particles at the crack tip and by the compressive back stress on the crack walls behind the tip, due to volume expansion associated with transformation to the monoclinic phase.

[0006] The well-known transformation toughening mechanism is operative in zirconia ceramics whose composition and production are optimized such that most of the grains have the tetragonal crystal structure. These zirconias are referred to as tetragonal zirconia

polycrystal (TZP) ceramics and their mechanical properties in air at room temperature are superior to those of zirconia-toughened aluminas and to other classes of zirconias. To the knowledge of the inventors, the biocompatibility of TZPs has not been fully assessed. However, the biocompatibility of the TZP has been at least preliminarily investigated.

[0007] For example, in one study by Thompson and Rawlings [see I. Thompson and R.D. Rawlings, "Mechanical Behavior of Zirconia and Zirconia-Toughened Alumina in a Simulated Body Environment," *Biomaterials*, 11 [7] 505-08 (1990)]. The results that TZP demonstrated a significant strength decrement when aged for long periods in Ringer's solution and was therefore unsuitable as implant material.

[0008] Drummond [see J.L. Drummond, *J. Amer. Ceram. Soc.*, 72 [4] 675-76 (1989)] reported that yttria-stabilized zirconia demonstrated low-temperature degradation at 37°C with a significant decrement in strength in as short as period as 140 to 302 days in deionized water, saline, or Ringer's solution. He also reports on similar observation by others, where yttria-doped zirconia demonstrated a strength decrement in water vapor, room temperature water, Ringer's solution, hot water, boiling water, and post-*in vivo* aging.

[0009] TZP components suffer a decrement in strength properties after exposure for only a few days to humid environments. This degradation of mechanical properties occurs when moisture is present in any form, for example, as humidity or as a soaking solution for the TZP component. TZP components have been observed to spontaneously fall apart after times as short as a few weeks in room temperature water. This is of particular importance in living-tissue implanted devices that contain components made of this class of material. Successful long-term implantation of devices that contain yttria-stabilized zirconia components is not feasible.

SUMMARY OF THE INVENTION

[0010] In one aspect, the invention provides a method of producing a stabilized tetragonal zirconia polycrystal sintered ceramic body, comprising the step of hot isostatic pressing (HIP) of the sintered ceramic body to increase the bulk density thereof.

[0011] Preferably, after the hot isostatic pressing the ceramic body has an average grain size of less than about 0.5 μm . High levels of bulk density can be achieved, even substantially 100% of theoretical bulk density. Preferably, after the hot isostatic pressing, the ceramic body has a bulk density of at least 6.05 g/cm³.

[0012] Typically the stabilized tetragonal zirconia polycrystal ceramic is stabilized with yttria, but other stabilizing additives may be used, alone or with yttria. For example, the ceramic is stabilized with 3 mole percent of yttria.

[0013] One form of the product of this method is an implantable hollow tube. Preferably this tube has a

length less than 100 mm, an outside diameter less than 10 mm and a wall thickness less than 2 mm.

[0014] Suitably the hot isostatic pressing is performed at at least 1000°C, preferably in the range 1200°C to 1450°C.

[0015] In the hot isostatic pressing the pressure is preferably at least 100 MPa. The hot isostatic pressing may be in an atmosphere of argon, or in an atmosphere of a mixture of 80 volume percent argon and 20 volume percent oxygen. The hot isostatic pressing is preferably conducted at the desired temperature and pressure for at least 30 minutes.

[0016] Preferably the sintered ceramic body before hot isostatic pressing has an open porosity of less than 2%. After the hot isostatic pressing, the porosity may be substantially eliminated. The tetragonal stabilized zirconia body is sintered, so as to produce the tetragonal stabilized crystal structure, before being subjected to the hot isostatic pressing step. Between these two steps, there may typically be other steps, e.g. cooling, and/or machining.

[0017] In another aspect, the invention provides a method of producing a living tissue implantable microstimulator substantially encapsulated within a hermetically-sealed housing, the housing comprised of a tetragonal zirconia polycrystal ceramic hollow tube produced by the method described above, and being for example of a size approximately 10 mm in diameter and 100 mm in length, and being of longitudinal shape capable of implantation in the immediate vicinity of selected areas of the body by expulsion through a hypodermic needle, including hermetically sealing a first inert, metallic electrode to the housing at or near one end thereof and a second inert, metallic electrode to the housing at or near another end thereof, a substantial portion of the electrodes being exposed outside the microstimulator so as to provide stimulation pulses.

[0018] Further there is provided a method of producing an implantable case, comprising producing the case as a stabilized tetragonal zirconia polycrystal ceramic by the above method, the implantable case being sized to have a length less than 100 mm, an outside diameter less than 10 mm and a wall thickness less than 2 mm; polishing the ceramic case to a surface finish of less than 32 microinch roughness; and

brazing hermetically sealed metal ends on the implantable case.

[0019] The method of the invention may include the step of loading the implantable case in three-point bending to a stress of at least 800 MPa to assure that said case will not fail at a lesser stress.

[0020] The invention also provides an implantable microstimulator comprised of:

a hermetically sealed case which is inert to body fluids;
said microstimulator being for example of a size approximately 6 mm in diameter and 60 mm in length

and of longitudinal shape capable of implantation in the immediate vicinity of selected areas of the body by expulsion through a hypodermic needle;

the case being comprised of stabilized tetragonal zirconia polycrystal ceramic produced by the method of the invention;

the case further having metal end caps that are brazed to said ceramic.

[0021] In another aspect, the invention consists in a method of producing a long-lived, stabilized tetragonal zirconia polycrystal ceramic, comprising the step of hot isostatic pressing said ceramic at a controlled temperature, at a controlled pressure, and in a controlled atmosphere to achieve an average grain size of less than about 0.5 micron, to substantially eliminate open porosity and to increase bulk density to about 100% of theoretical, thereby substantially eliminating low-temperature degradation of said implantable case.

[0022] Further, the invention provides a method of producing a long-lived, implantable case, said implantable case comprised of a stabilized tetragonal zirconia polycrystal ceramic, wherein the improvement comprises the step of hot isostatic pressing said implantable case at a controlled temperature, at a controlled pressure, and in a controlled atmosphere to achieve an average grain size of less than about 0.5 micron, to substantially eliminate open porosity and to increase bulk density to about 100% of theoretical, thereby substantially eliminating low-temperature degradation of said implantable case. The case may be a hollow tube having for example a length less than 100 mm, an outside diameter less than 10 mm and a wall thickness less than 2 mm.

[0023] In another aspect, the invention provides a method of producing a long-lived, living tissue implantable microstimulator substantially encapsulated within a hermetically-sealed housing, said housing comprised of an yttria-stabilized tetragonal zirconia polycrystal ceramic hollow tube, said microstimulator being for example of a size approximately 10 mm in diameter and 100 mm in length and of longitudinal shape capable of implantation in the immediate vicinity of selected areas of the body by expulsion through a hypodermic needle, a first inert, metallic electrode hermetically sealed to said housing at or near one end thereof and a second inert, metallic electrode hermetically sealed to said housing at or near another end thereof, and a substantial portion of said electrodes being exposed outside said microstimulator so as to provide stimulation pulses, wherein the improvement comprises the step of hot isostatic pressing said yttria-stabilized tetragonal zirconia polycrystal ceramic hollow tube at a controlled temperature, at a controlled pressure, and in a controlled atmosphere to achieve an average grain size of less than about 0.5 micron, to substantially eliminate open porosity and to increase bulk density to about 100% of theoretical, thereby eliminating low-temperature degradation of said

ceramic hollow tube.

[0024] Yet another aspect of the invention is a method of producing a long-lived, implantable case, said implantable case comprised of a stabilized tetragonal zirconia polycrystal ceramic, comprising the steps of:

forming said implantable case sized to have for example a length less than 100 mm, an outside diameter less than 10 mm and a wall thickness less than 2 mm;

sintering said case to an open porosity of less than 2%;

hot isostatically pressing said implantable case at a controlled temperature, at a controlled pressure, and in a controlled atmosphere to achieve an average grain size of less than about 0.5 micron, to substantially eliminate open porosity and to increase bulk density to about 100% of theoretical, thereby substantially eliminating low-temperature degradation of said implantable case;

polishing said ceramic tube to a surface finish of less than 32 microinch roughness; and
brazing hermetically sealed metal ends on said implantable case.

[0025] The invention also provides a ceramic which is inert to water comprised of:

said ceramic comprised of stabilized tetragonal zirconia polycrystal ceramic;

wherein said ceramic is comprised of a sintered ceramic;

wherein said ceramic is comprised of a hot isostatically pressed ceramic that has been pressed at a pressure in a gas environment for a controlled time in a controlled temperature; and

wherein said ceramic is comprised of a tetragonal phase zirconia.

[0026] Further, the invention provides an implantable microstimulator comprised of:

a hermetically sealed case which is inert to body fluids;

said microstimulator being of a size approximately 6 mm in diameter and 60 mm in length and of longitudinal shape capable of implantation in the immediate vicinity of selected areas of the body by expulsion through a hypodermic needle;

said case comprised of stabilized tetragonal zirconia polycrystal ceramic;

said case further comprised of metal end caps that are brazed to said ceramic;

wherein said case is comprised of a sintered ceramic;

wherein said case is comprised of a hot isostatically pressed ceramic that has been pressed at a controlled

pressure in a controlled gas at a controlled temperature for a controlled time; and

wherein said case is comprised of a tetragonal phase zirconia, said case having an implant life exceeding 50 years.

BRIEF DESCRIPTION OF THE DRAWINGS

[0027]

FIG. 1 presents the microstimulator.

FIG. 2 presents the ceramic processing method steps to form the improved material.

FIG. 3 presents the hot isostatic pressing method steps.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0028] A broadly applicable material and method of producing the improved material has been developed. It has been demonstrated that hot isostatic pressing a sintered yttria-stabilized tetragonal zirconia polycrystalline ceramic (Y-TZP) dramatically reduces the destructive phase transformation from tetragonal to monoclinic. While this material and the method of production are widely applicable, a preferred embodiment is to apply this invention to implantable devices that are suitable for use as implants in living tissue, an application previously prohibited to this class of ceramic material.

[0029] A novel ceramic to metal brazed case has been designed for implantable microstimulator, such as the microstimulator of Advanced Bionics Corporation, 12740 San Fernando Road, Sylmar, California. U.S. Patents No. 5,193,540 and 5,324,316 present developments related to this microstimulator and are incorporated in their entirety by reference herein. Yttria stabilized-TZP (Y-TZP) has been selected as the ceramic material because of its high strength, favorable fracture toughness, and biocompatibility. It provides a hermetic and robust housing for the electronic module located inside.

[0030] The strength decrement in humid environment varies among Y-TZP ceramics, depending upon the quality of the ceramic and its composition. This variability is related to the differences in equilibrium of microstructural parameters such as: concentration and distribution of phase stabilizer, grain size, flaw population and distribution, residual stress, density, etc.

[0031] A preferred microstimulator 2 is presented in FIG. 1, wherein a hollow ceramic tube 4 is preferably attached by brazing to an electrode 6 on either end of the microstimulator 2, thereby forming a hermetically sealed hollow enclosure suitable to contain electronics for either sensing or stimulating living tissue into which the microstimulator 2 may be implanted. The size of the microstimulator 2 is preferably approximately 10 mm or less in diameter and 100 mm or less in length, preferably

less than 6 mm in diameter and 60 mm in length, and of longitudinal shape capable of implantation in the immediate vicinity of selected areas of the body by expulsion through a hypodermic needle or other implantation device.

[0032] The ceramic tube 4 is comprised of a strong, hermetic material that is biocompatible, such as Y-TZP. In alternative embodiments, other stabilizer materials may be utilized in place of yttria, such as ceria, magnesia, calcia, hafnia, or other known stabilizing additives.

[0033] The Y-TZP ceramic tube 4 is formed by conventional ceramic forming processes as shown in FIG. 2, preferably including pressing 22 and sintering 24. The method of forming the tube includes raw material preparation 20, which includes particle size control and binder selection and introduction, as well as selecting the yttria powder and stabilizer. Post-sintering the dense ceramic is optionally machined 26 to final dimensions and required surface finish. The ceramic tube 4 is next further processed by hot isostatic pressing (HIPping) 28 or other known densification methods.

[0034] The dense formed ceramic tube 4 is processed according to FIG. 3, where the part is processed 32 by cleaning and is placed in a vacuum 34. The ceramic tube 4 is then heated 36 to 1200°C to 1450°C and inert gas is placed in the chamber. It is preferred that argon be used, although other inert gasses may also be selected, as well as selecting a mixture of an inert gas and oxygen, preferably 80 volume percent argon and 20 volume percent oxygen. The chamber is pressurized 40 to preferably approximately 100 MPa, although higher pressures may be utilized to achieve optimum materials properties, and the part is held at temperature and pressure for approximately 30 minutes, although shorter or longer hold times may alternatively be used depending on the selected temperature and pressure. The process chamber and ceramic tube 4 are cooled 44 and the tube 4 is removed and is ready for assembly into the microstimulator 2.

[0035] The finished ceramic tube 4 has been post-processed examined to assure that the low-temperature phase transformation has been controlled. Sealed empty brazed cases were used in the *in vitro* accelerated aging test. Aging treatments were carried out in temperature-controlled ovens and in autoclaves. Low-temperature ceramic degradation was quantified by determining the monoclinic volume fraction (X_m) on the ceramic surface of the finished ceramic tube 4. X_m was measured using an X-ray diffraction (XRD) technique and its volume content was calculated from the modified Garvie-Nicholson equation, i.e., $X_m = I_m / (I_m + I_t)$, where I_m is the area under the peak curve for monoclinic phase zirconia as measured by XRD techniques and I_t is the area under the peak curve for tetragonal phase zirconia.

Example 1

[0036] As-sintered ceramic tubes having a length of

11.7 mm, an outside diameter 2.3 mm and a wall thickness of 0.5 mm and hot isostatically pressed (HIPped) ceramic tubes having the same size and made in the same batch were soaked in 127°C steam. X-Ray Diffraction was used to measure the surface monoclinic phase and the monoclinic volume fraction was calculated from the modified Garvie-Nicholson equation.

[0037] After soaking in 127°C steam for 171 hours, the monoclinic content on the surface of as-sintered ceramic tubes reached 35% from its original monoclinic content of 2.0%. After the same period of time soaked in the same environment, the monoclinic content on the HIPped ceramic tubes reaches 22% from 0.6% prior to soaking.

[0038] XRD analysis showed that although both HIPped and as-sintered ceramics are subject to moisture-induced tetragonal to monoclinic phase transformation, the transformation rate in HIPped TZP was significantly slower than that demonstrated by non-HIPped TZP.

[0039] The HIPping process virtually eliminated porosity of the sintered material, improving flexural strength and fracture toughness. The HIPping operation enhanced the aging resistance. The HIPped Y-TZP is much denser than the as-sintered TZP material, with measured bulk density of about 6.05 g/cm³, compared to the specific gravity of 6.10.

[0040] As an additional post-HIPped process, the ceramic tube may be loaded in a flexural bending mode so as to pre-load the tube at a known stress. The stress for this proof test type of qualification is preferably 800 MPa, although higher or lower stresses may be used to either change the acceptance rate or to assure a different minimum failure strength. Because of the small size of the tube, three-point bending is utilized to pre-load the tube, although four-point bending would preferably be used with a longer sample. Tubes that fail to survive the pre-load are thus culled from the sample population thereby giving a minimum strength for the survivors.

[0041] Obviously, many modifications and variations of the present invention are possible in light of the above teachings. It is therefore to be understood that, the invention may be practiced otherwise than as specifically described.

Claims

1. A method of producing a stabilized tetragonal zirconia polycrystal sintered ceramic body, comprising the step of hot isostatic pressing said sintered ceramic body to increase the bulk density thereof.
2. The method according to claim 1, wherein after the hot isostatic pressing the ceramic body has an average grain size of less than about 0.5 μm.
3. The method according to claim 1 or 2, wherein after

the hot isostatic pressing, the ceramic body has a bulk density of at least 6.05 g/cm³.

4. The method according to any one of claims 1 to 3, wherein said stabilized tetragonal zirconia polycrystal ceramic is stabilized with yttria. 5
5. The method according to claim 4, wherein said ceramic is stabilized with 3 mole percent of yttria.
6. The method according to any one of claims 1 to 5, wherein said ceramic body is an implantable hollow tube.
7. The method according to claim 6, wherein said hollow tube has a length less than 100 mm, an outside diameter less than 10 mm and a wall thickness less than 2 mm. 15
8. The method according to any one of claims 1 to 7, wherein the hot isostatic pressing is performed at at least 1000°C. 20
9. The method according to any one of claims 1 to 8, wherein the hot isostatic pressing is performed in the range 1200°C to 1450°C. 25
10. The method according to any one of claims 1 to 9, wherein the hot isostatic pressing is at a pressure of at least 100 MPa. 30
11. The method according to any one of claims 1 to 10, wherein the hot isostatic pressing is in an atmosphere of argon. 35
12. The method according to any one of claims 1 to 10, wherein the hot isostatic pressing is in an atmosphere of a mixture of 80 volume percent argon and 20 volume percent oxygen. 40
13. The method according to any one of claims 1 to 12, wherein the sintered ceramic body before hot isostatic pressing has an open porosity of less than 2%. 45
14. The method according to any one of claims 1 to 13, wherein said hot isostatic pressing is conducted at the desired temperature and pressure for at least 30 minutes. 50
15. A method of producing a living tissue implantable microstimulator substantially encapsulated within a hermetically-sealed housing, said housing comprised of a tetragonal zirconia polycrystal ceramic hollow tube produced according to any one of claims 1 to 14, and being of a size approximately 10 mm in diameter and 100 mm in length and of longitudinal shape capable of implantation in the im-

mediate vicinity of selected areas of the body by expulsion through a hypodermic needle, including hermetically sealing a first inert, metallic electrode to said housing at or near one end thereof and a second inert, metallic electrode to said housing at or near another end thereof, a substantial portion of said electrodes being exposed outside said microstimulator so as to provide stimulation pulses.

- 10 16. A method of producing an implantable case, comprising producing said case as a stabilized tetragonal zirconia polycrystal ceramic by the method of any one of claims 1 to 14, said implantable case being sized to have a length less than 100 mm, an outside diameter less than 10 mm and a wall thickness less than 2 mm; 15
 polishing said ceramic case to a surface finish of less than 32 microinch roughness; and
 brazing hermetically sealed metal ends on said implantable case. 20
17. The method of claim 16, further comprising the step of loading the implantable case in three-point bending to a stress of at least 800 MPa to assure that said case will not fail at a lesser stress. 25
18. An implantable microstimulator comprised of: 30
 a hermetically sealed case which is inert to body fluids;
 said microstimulator being for example of a size approximately 6 mm in diameter and 60 mm in length and of longitudinal shape capable of implantation in the immediate vicinity of selected areas of the body by expulsion through a hypodermic needle; 35
 said case being comprised of stabilized tetragonal zirconia polycrystal ceramic produced by a method of any one of claims 1 to 14;
 said case further having metal end caps that are brazed to said ceramic. 40

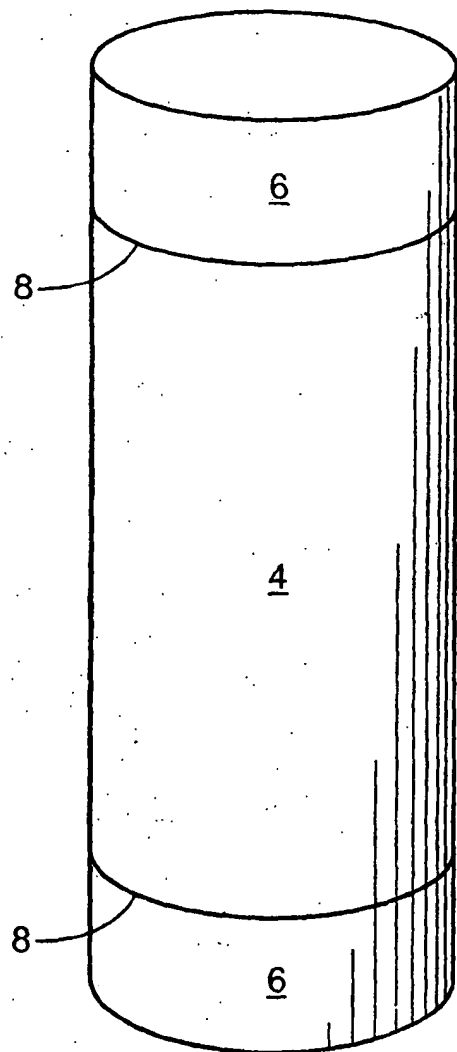


Fig. 1

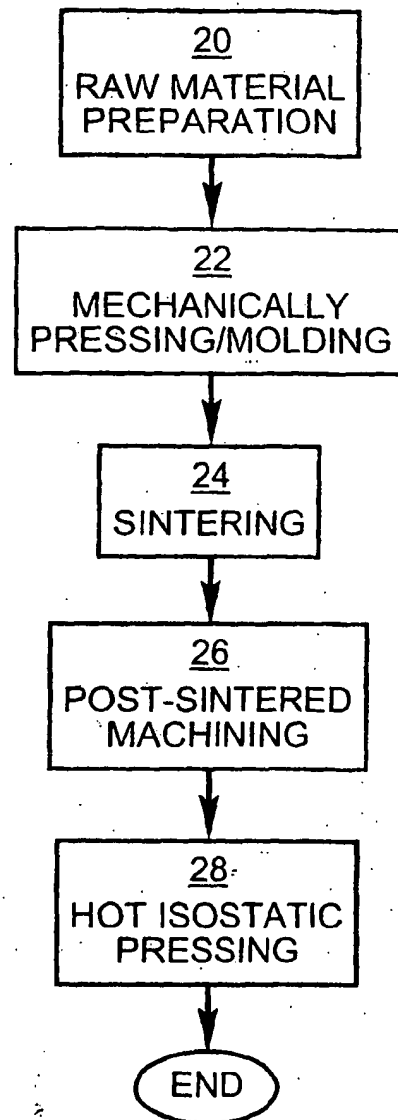


Fig. 2

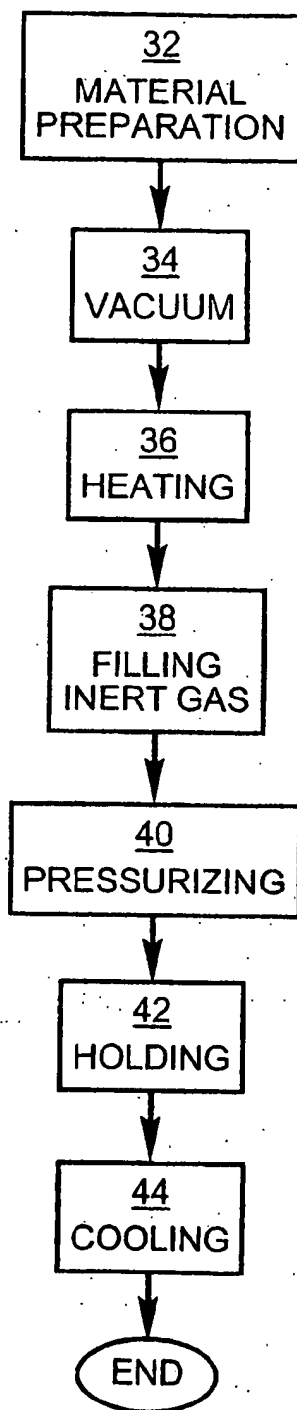


Fig. 3



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EUROPEAN SEARCH REPORT

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Place of search Munich		Date of completion of the search 14 June 2004	Examiner Vathilakis, S
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document			

**ANNEX TO THE EUROPEAN SEARCH REPORT
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